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Turbulent Mixing in Aquatic Microcosms

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Turbulent Mixing in Aquatic Microcosms

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ABSTRACT

On the basis of theoretical considerations and a small body of available empirical evidence, the rate of dissipation of turbulent mixing energy appears to influence the behavior and physiology of plankton in marine and freshwater ecosystems. However, because of technical difficulties in measuring turbulence, there has generally been little effort to consider this feature in designing microcosms as analogues of natural systems. In the relatively large (13-m^3) microcosms at the Marine Ecosystems Research Laboratory at the University of Rhode Island, a mechanical mixing device was included in an attempt to provide a turbulence regime that is appropriate for plankton from Narragansett Bay, a shallow (9-m), well-mixed estuary. The characteristics of water mixing and turbulent energy dissipation in the microcosms are described and compared with the bay by use of a number of measures, including dye tracers, $CaSO_4$ dissolution rates, freshwater and saltwater mixing studies, air–sea gas-exchange properties, and neighbor diffusivity estimates obtained from paired floats. The rate of vertical water mixing appears to be considerably more rapid in the tanks than in Narragansett Bay, but the horizontal turbulent field appears to be less than that generally found in near-shore marine waters. In both the microcosms and the natural system, the amount of energy passing through the biological system appears to be greater than that dissipated by the physical system in turbulent water mixing.

Although there is general agreement that it is impossible and unnecessary for any microcosm to be an exact replica of any natural system, most of us who work with living models feel more confident of experimental results obtained from them if the major features of the microcosm coincide as closely as possible with those of the

natural environment of interest. Despite the fact that microcosm studies have contributed to the development of a number of general ecological principles (Beyers, 1963; Cooke, 1967; Odum, 1969), it is intuitively more satisfying to study the ecology of coastal marine waters with large tanks or bags of seawater and marine sediments than to extrapolate from carboys of lake water, experimental salt-marsh plots, or even small flasks of seawater. Even within a particular type of ecological system, it is possible to show that the behavior of the experimental community is influenced by the design of the microcosm used in the study. It follows that considerably more attention should be paid to the physical and biological scaling of living models (Perez et al., 1977; Nixon et al., 1979; Oviatt et al., 1979).

The design of a pelagic coastal marine microcosm is particularly challenging because of the difficulties in scaling surface-to-volume ratios, water volume to sediment surface area, light profiles, spatial variability, and advection and turbulent mixing. Although it is difficult or impossible to design a microcosm that precisely mimics the coastal marine environment with regard to any of these or other parameters, it should, in principle, be relatively easy to quantify and compare most of them. This is not the case with turbulent mixing, however, which, until very recently, has been virtually ignored in such studies. This is not surprising since the nature of turbulent energy dissipation in marine waters is one of the most difficult areas of fluid dynamics (Okubo, 1971), and there have been very few field or laboratory studies of the effect of turbulence on the behavior or physiology of pelagic organisms. Nevertheless, both theoretical considerations (Nixon, Oviatt, and Buckley, 1979) and a growing body of empirical data suggest that water turbulence can be an important feature of the real world for marine plankton (Pasciak and Gavis, 1975; Perez et al., 1977; Nixon, Oviatt, and Buckley, 1979). A growing awareness of the potential importance of turbulent mixing in aquatic systems led to recent first attempts to characterize some features of the mixing obtained in microcosms of varying design, including very large (1300-m^3) plastic bags (Steele, Farmer, and Henderson, 1977), flexible benthic "bell jar" metabolic chambers (Gust, 1977), and 150-liter laboratory tanks (Nixon, Oviatt, and Buckley, 1979). This paper describes the mixing device used in 12 large (13-m^3) saltwater microcosms at the Marine Ecosystem Research Laboratory (MERL) at the University of Rhode Island and attempts to develop and apply a number of techniques to compare the turbulence obtained in the microcosms with that generated by wind and tides in adjacent Narragansett Bay.

NARRAGANSETT BAY AND THE MERL MICROCOSMS

Narragansett Bay—The Reference System

The Marine Ecosystems Research Laboratory (MERL), with 12 large tank microcosms, was built on the shore of the lower West Passage of Narragansett Bay (Fig. 1). This location is adjacent to a natural coastal marine system that is one of the most thoroughly studied bodies of water in the world. Although we have never tried to produce an exact replica of the bay in our microcosm tanks, we use the bay as a reference system that can be compared and contrasted with the microcosms to provide a useful perspective.

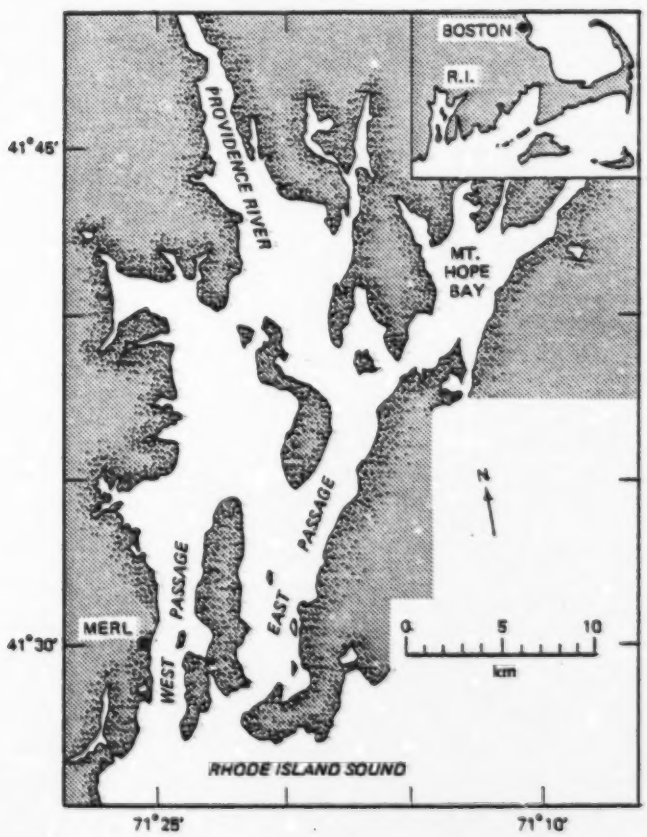

Fig. 1 Location of MERL on Narragansett Bay.

Since the microcosms are designed to study the dynamics of shallow, plankton-based coastal waters and associated bottom communities similar to those found in the bay and since the microcosms contain water and sediments taken from the bay, we would prefer that the biology and chemistry of the tanks be reasonably similar to those in the field. The success of our efforts in this regard is the subject of other papers (Pilson et al., 1977, 1979, and this volume; Marine Ecosystems Research Laboratory, 1979). In general, we are convinced that the microcosms are a useful ecological analogue of Narragansett Bay. Until recently, however, we have had virtually no data to use in comparing the turbulent mixing regimes in the two systems.

During the design phase of MERL, the consensus of opinion among everyone involved in the project was that the microcosms ought to be stirred in some fashion. However, the complexity of the problem of producing in a 2-m-diameter by 5.5-m-deep tank a turbulent field similar to that produced in Narragansett Bay by tides and winds prevented us from developing any practical theoretical framework with which to address the design of a mixing device. Also there were no measurements of turbulence in the bay that could be used empirically to calibrate the microcosms. Therefore we took a pragmatic approach in designing and constructing a mixing system that was reasonably flexible in its operation. The only design criteria we had to begin with were that the device be able to produce a well-mixed water column with no vertical stratification or gradients; that the mixer be capable of resuspending sediment from the bottom of the tank to produce levels of suspended material in the water column which are similar to those in the bay, and that the device create a current across the bottom sediment sufficient to maintain the benthos in viable condition.

These criteria were selected for a number of reasons. First, Narragansett Bay receives little freshwater input (annual mean of 37 m^3/sec). Thus the semidiurnal tidal currents (mean tidal range at the mouth of the bay is about 1.1 m) and wind produce a relatively well-mixed water column that shows only slight vertical stratification, especially in the lower bay (Hicks, 1959; Kremer and Nixon, 1978). Second, a substantial amount of information is already available on suspended sediment in the bay (Morton, 1972; Collins, 1974; Oviatt and Nixon, 1975). It seemed clear that suspended sediment would be an important parameter influencing light penetration and a number of chemical pathways. Third, the special case of the importance of turbulent flow for sessile bottom animals and plants was already well established (Kerswill, 1949; Jaag and

Ambuhl, 1963; Westlake, 1967; Nixon et al., 1971). Since neither the tides nor the wind provides a constant input of turbulent energy to the bay, we decided that the mechanical mixing of the microcosms should operate in an on—off mode so that the benthos might sense a varied current regime and there would be periods of relative quiet when suspended matter might settle.

Microcosm Tanks and the Mixing Regime

Microcosm Tanks

The MERL microcosms consist of an open-air tank farm of 12 2-m-diameter by 5.5-m-deep double-wall insulated fiberglass tanks (Fig. 2) located by the West Passage of Narragansett Bay, Rhode Island. Natural benthic communities representative of Narragansett Bay are placed in containers in the bottom of each microcosm, and the tanks are filled with seawater from Narragansett Bay, with periodic 100-liter replacements to produce a complete turnover in ~30 days. The depth of the tanks was calculated to be sufficient that when they were filled with bay water the benthos would receive < 1% of the surface illumination. The diameter of the tanks is large enough that the benthic tray provides a year's worth of nonoverlapping benthic samples. The insides of the tanks were colored white to reflect as much light as possible. The water column is stirred to simulate natural environments, and the temperature within the tanks can be controlled by heat exchangers immersed in the water column. Table 1 shows the characteristic dimensions of the microcosms.

Mixing Regime

Mixing energy is introduced into the water by a plunger (Fig. 2), a solid body 50 cm in diameter with a streamlined upper surface and a flat lower surface. It is located in the lower part of the water column and moves in a vertical-plane elliptical orbit, 60 cm on its vertical axis and ~1 m on its horizontal axis. Its motion is transmitted through a 4.8-m-long PVC shaft connected to a 30-cm-long crank located directly over the center of the tank. The crank is driven by a variable-speed electric motor. A set of 7 motors is used to drive 12 mixers (5 duplex, 2 simplex) in the existing MERL installation. The mixers are normally operated for a period of 2 hr at approximately 5 rpm after which there is a 4-hr period with no mixing. This cycle is repeated continually, except during cleaning or certain sampling operations. The intention was that this cycle would mimic the alternately fast-running and relatively slow tidal

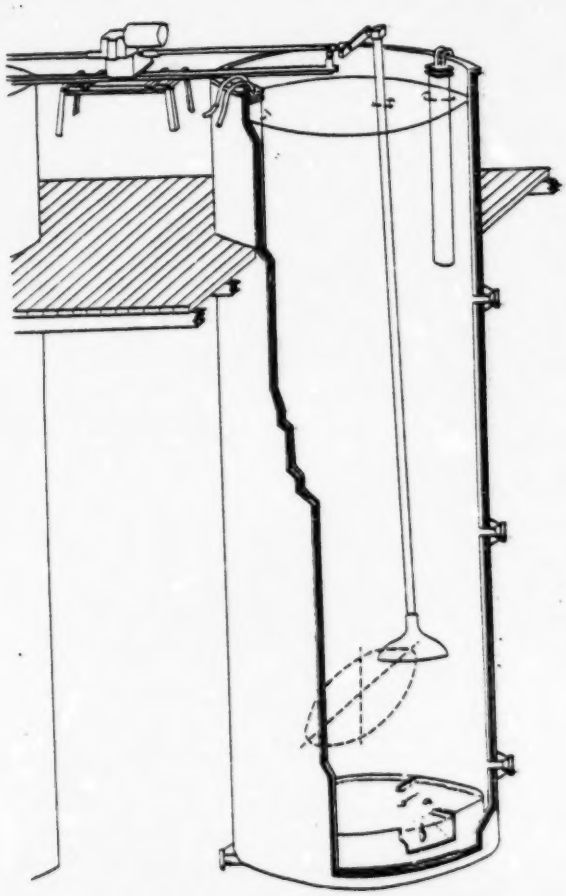

Fig. 2 Cutaway view of a MERL microcosm showing locations of heat exchangers hung from the upper edge of the tank, sampling ports on the side of the tank at various depths, the sediment container on the bottom, and the mixer device. The mixer motor is located between tanks, and the crank, shaft, and "plunger" are near the centerline of the tank. The plunger moves in a vertical ellipse (shown in dashed lines).

TABLE 1

PHYSICAL CHARACTERISTICS OF MERL MICROCOSMS

Tank	
Interior diameter	1.83 m
Interior height	5.49 m
Walls, white fiberglass resin with about 5 cm of polyurethane foam insulation	
Water	
Depth	5.00 m
Surface area	2.63 m^2
Volume, net	13.1 m^3
Salinity, usual	29—30‰
Mass	13.4 tons
Sediment	
Surface area	2.52 m^2
Depth	0.30 m
Volume	0.756 m^3
Mass (wet)	1.10 tons
Mass (dry)	0.568 tons
Mixer	
Motor power, rated maximum	560 W
Electrical input	0—90 V d-c
Plunger diameter	50 cm
Volume of plunger	0.0156 m^3
Vertical excursion	60 cm

currents in the bay, allowing periods of sediment resuspension and settling.

The plunger reaches to within 60 cm of the sediment surface and produces a net flow of water downward over the sediment, as well as eddy currents that extend throughout the entire water column. These water motions, although quite different from tidal motions, meet the design criteria previously mentioned. The system is relatively simple, inexpensive, and easy to maintain. During the past year or so, we have attempted to gain insight into the energy dissipation rate associated with the mixing regime and the nature of the mixing processes within the tanks and to obtain comparative measurements from Narragansett Bay.

TURBULENCE MEASUREMENTS

Direct Calculation

One straightforward approach to estimating the mixing energy in the microcosms would be to calculate from measured current and voltage drop the electrical power used by the motors driving the mixers. For a motor driving two mixers, this amounted to 112 W or 5.6×10^8 ergs/sec per mixer. Since each tank contains a water mass of 13.4×10^6 g, the electrical energy expended amounts to about 42 ergs g^{-1} sec^{-1}. Without the mixers attached, the electrical power approximated 102 W; thus the power associated with each mixer was about 5 W or 3.7 ergs g^{-1} sec^{-1}. Unfortunately, the mixing system includes a reduction gear and a number of bearings. We believe that by far the greatest fraction of the energy is expended in overcoming frictional losses. Moreover, these losses vary with the weight of the mixer during a rotation of the shaft, so that the energy input to the tanks cannot be estimated from the consumption of electrical power.

We can get a rough estimate of the energy imparted to the water by the mixer by calculating from estimates of the volume of water accelerated by the plunger as follows:

Diameter of plunger = 50 cm; vertical excursion = 60 cm
Volume of water swept by plunger (one-half cycle) = 117,800 cm^3
Frequency = 4.8/min, or one full cycle in 12.5 sec
Maximum velocity (down or up) = 15.1 cm/sec
Time to reach maximum velocity = 3.125 sec (one-fourth cycle)

Assuming that the volume of water accelerated to 15.1 cm/sec is equal to the swept-out volume of water for one-half cycle and taking acceleration as linear, we find that the force required is

$$\left(\frac{15.1 \text{ cm/sec}}{3.125 \text{ sec}}\right)(120{,}000 \text{ g}) = 580{,}600 \text{ g cm sec}^{-2} \text{ (dynes)}$$

This force, acting over 30 cm on each one-half cycle and over 60 cm on each full cycle, results in an expended energy of

$$\frac{(580{,}600 \text{ g cm sec}^{-2})\,(60 \text{ cm})}{12.5 \text{ sec}} = 2.79 \times 10^6 \text{ g cm}^2 \text{ sec}^{-3}$$

Dividing by the mass of water in the whole tank gives a total energy expended of

$$\frac{2.79 \times 10^6 \text{ g cm}^2 \text{ sec}^{-3}}{13.4 \times 10^6 \text{ g}} = 0.21 \text{ cm}^2 \text{ sec}^{-3}$$

or 0.21 ergs g^{-1} sec^{-1}

We intend to make direct measurements of the drag of the plunger through the water. Cyclic accelerations of motion and various lateral motions of the plunger introduce sufficient complexity, however, that we expect difficulties in making an absolute measurement of the turbulent energy introduced into the water by the plunger. In the meantime, the estimate of 0.21 ergs g^{-1} sec^{-1} provides a rough approximation of the energy dissipation associated with mixing and turbulent processes in the tanks and is likely to be correct within an order of magnitude.

Mixing of a Pycnocline

A minimum estimate of the turbulent energy introduced into the water column is provided by measurements of the mixing of a pycnocline. Unlike most other measures of turbulence, the minimum energy required to accomplish this is a readily calculated physical quantity. The procedure does not, however, measure the simultaneous energy dissipation by other mechanisms within the water column and along the tank walls and bottom.

The procedure can be described generally as follows. A MERL tank is filled with a layer of salt water and a layer of fresh water (Fig. 3), or a thermocline is produced by raising the temperature of the surface water with the heat exchangers (Fig. 2). The mixer is allowed to operate in the normal manner. The turbulent energy introduced into the tank by the plunger will be dissipated by (1) frictional loss within the salt water (through the cascading of energy to ever smaller eddies and finally viscous decay), (2) frictional loss against the bottom, the sides, and the plunger itself, (3) frictional loss against the pycnocline (to the extent that it acts as a wall), and (4) erosion of the pycnocline to the final point where the fresh water and salt water are completely mixed. Although motions of the shaft of the plunger must have some effect on the pycnocline, it seems likely that most of the pycnocline destruction is caused by turbulent energy generated by the plunger impinging upwards on this "surface." In any case, the shaft itself is also a source of turbulent energy and contributes to the total input. The energy required to mix the different layers and the time taken can be combined to produce a simple minimum estimate of the energy dissipation rate associated with mixing.

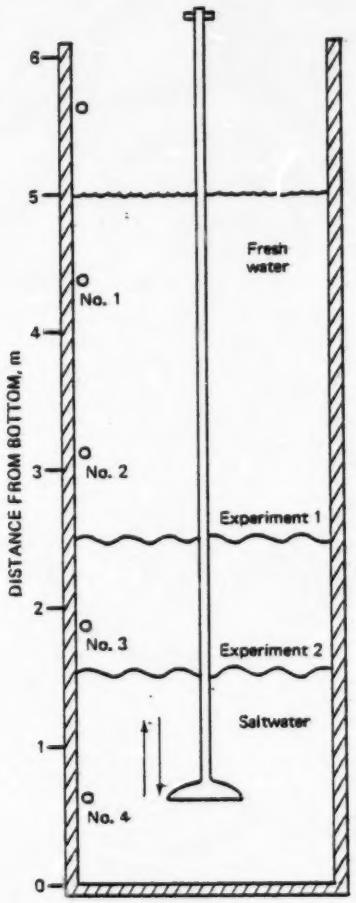

Fig. 3 Location of initial pycnoclines and sampling points for freshwater—saltwater mixing experiments.

Halocline Mixing Experiments

Experiments such as that described using strong and weak salinity gradients were carried out on Jan. 16 and Mar. 1, 1978, with similar results. In experiment 1 a fairly sharp salinity gradient was formed by placing a lower layer of bay water (salinity = 30‰) and an upper layer of fresh water in a MERL tank. With the mixer operating at 4.1 rpm, salinity and temperature were monitored at

TABLE 2

ANALYSIS OF THE FIRST FRESHWATER–SALTWATER MIXING EXPERIMENT IN A MERL MICROCOSM WITH A STRONG PYCNOCLINE

Time, hr	Δt, sec	Center of gravity (CG) location,* cm	ΔCG, cm	ε,† ergs g^{-1} sec^{-1}
0.70		0.513		
	7200		0.127	0.017
2.75		0.640		
	4248		0.067	0.016
3.93		0.707		
	2952		0.046	0.015
4.75		0.753		
	8712		0.129	0.014
7.17		0.882		
	6768		0.091	0.013
9.05		0.973		
	4752		0.060	0.012
10.37		1.033		
	5868		0.070	0.012
12.00		1.103		
	5688		0.059	0.010
13.58		1.162		
	5112		0.051	0.010
15.00		1.213		
	5400		0.048	0.009
16.50		1.261		
	5400		0.047	0.008
18.00		1.308		
	7632		0.057	0.007
20.12		1.365		
	7488		0.055	0.007
22.20		1.420		

*Distance above bottom of tank +248 cm.

† $\varepsilon = 981\ \text{cm/sec}^2 \dfrac{\Delta CG\ (\text{cm})}{\Delta t\ (\text{sec})}$

four locations (Fig. 3) for 22 hr. The density of the section of water column around each sampling point was calculated from these data and was used to determine the center of gravity of the water column (Table 2).

A time series of the location of the center of gravity was plotted, and a smooth curve was drawn by eye through the points (Fig. 4a). The rise in the center of gravity of the water column requires, as a

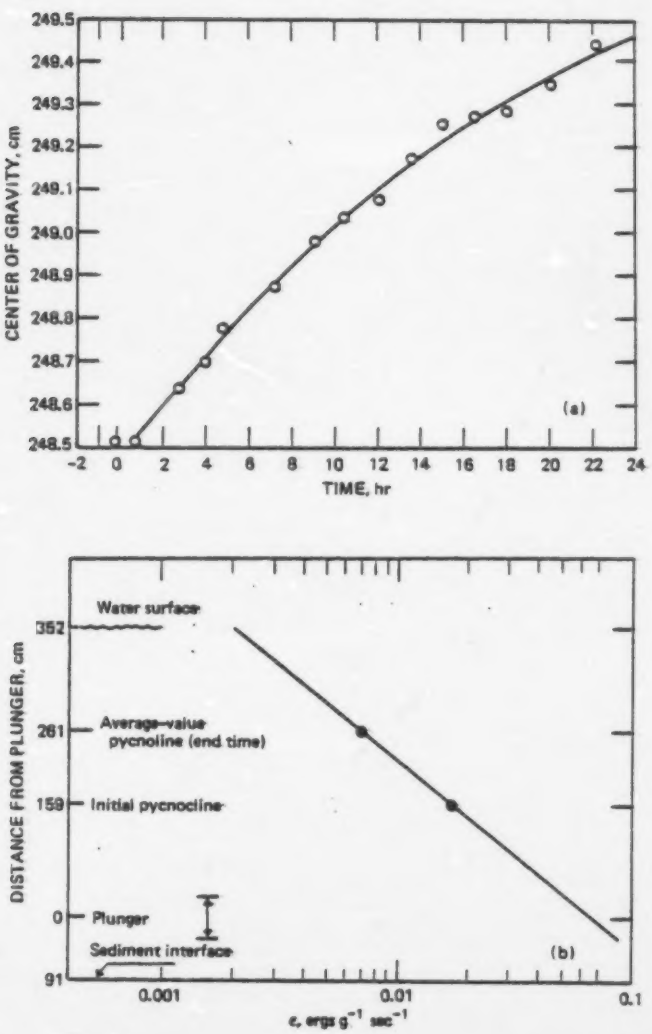

Fig. 4 (a) Changes in location of the water column center of gravity during pycnocline mixing experiment 1. (b) Estimate of range of energy dissipation rates due to pycnocline mixing in a MERL microcosm.

minimum, work equivalent to that of lifting 13.4×10^6 g of water the measured distance over each interval of time:

$$\frac{W}{t} = \frac{Fz}{t} = \frac{mgz}{t} \tag{1}$$

where W = work
F = force
z = distance
m = mass
g = acceleration of gravity
t = time

The energy dissipation rate, ϵ, is generally expressed per unit mass, however:

$$\epsilon = \frac{W}{mt} = \frac{gz}{t}$$

The slope of the curve in Fig. 4(a) gives the rate at which turbulent energy appears as potential energy. Since the total dissipation rate, ϵ, cannot be less, this estimate provides a lower boundary value for the energy input to the water. The total energy input, of course, must have been considerably greater.

For this experiment the minimum estimated ϵ was found to decrease with time (Table 2); this implies that as the pycnocline moved away from the main source of energy, the plunger, the rate at which it was eroded became smaller. Values of ϵ for this experiment ranged from 0.017 ergs g^{-1} sec^{-1} when the sharp pycnocline was 1.6 m from the plunger to 0.007 ergs g^{-1} sec^{-1} when the mean distance of a very diffuse pycnocline was 2.6 m from the plunger. Figure 4(b) shows extrapolations of these distances both toward the water surface and toward the plunger, assuming a logarithmic decay. Values of ϵ through the water column would then range from 0.002 at the surface to ~0.06 at the plunger.

In experiment 2 a homogeneous mixture of fresh water and bay water was introduced into the bottom of a MERL tank and fresh water was layered over it (Fig. 3); this resulted in a much weaker initial pycnocline. The mixer was turned on and allowed to run at a speed varying from 4.7 rpm initially to 4.9 rpm at the end of the experiment, when conditions near homogeneity were observed. Samples and measurements were taken at the same locations as in experiment 1 (Fig. 3).

Density (σ_t) calculated from temperature and salinity changed rapidly at sampling location 3 (Fig. 5); this suggests that the

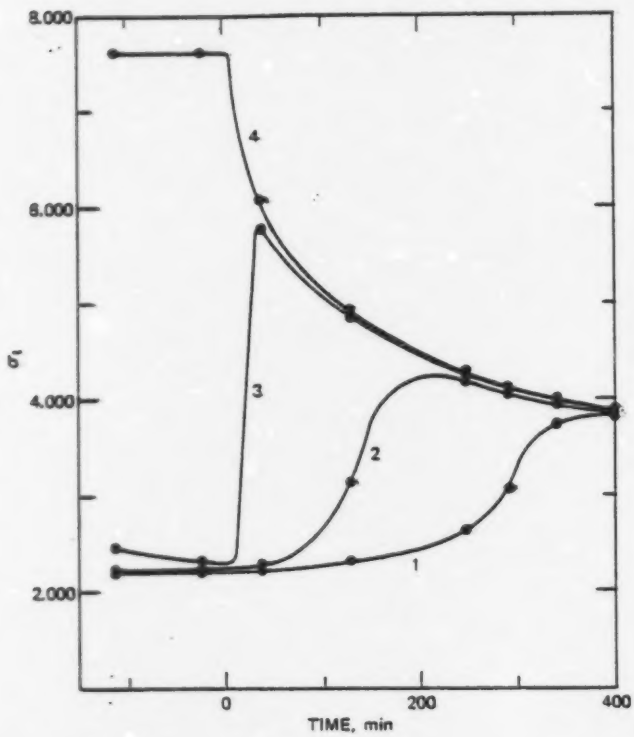

Fig. 5 Density changes vs. time at four sampling locations (see Fig. 3) for second freshwater—saltwater mixing experiment.

pycnocline was very close to that location at the beginning of mixing. Thus some mixing may have occurred at the interface during filling operations. However, even though the measurements taken initially do not define the exact thickness of each layer or the gradient of the pycnocline, a good approximation was obtained by assuming conservation of salt and estimating the total salt from the final measurements, when the gradients were minimal. Using the corrected thickness of each layer around each sampling point, we calculated the center of gravity of the entire water column for each sampling time (Table 3, Fig. 6). For comparison, uniform thickness layers were assumed around each sampling location, and the center of gravity was calculated for each sampling time. The differences between results from the two calculation procedures were small (Fig. 6).

TABLE 3

ANALYSIS OF THE SECOND FRESHWATER–SALTWATER MIXING EXPERIMENT IN A MERL MICROCOSM WITH A WEAK PYCNOCLINE

Time, min	Δt, sec	Center of gravity (CG) location,* cm	ΔCG, cm	ϵ,† ergs g^{-1} sec^{-1}
0		0.720		
	2340		0.052	0.022
39		0.772		
	5460		0.082	0.015
130		0.854		
	6840		0.075	0.011
244		0.929		
	2700		0.025	0.009
289		0.954		
	2940		0.022	0.007
338		0.976		
	3540		0.019	0.005
397		0.995		

*Distance above bottom of tank +249 cm.

†From smoothed curve. $\epsilon = 981 \text{ cm/sec}^2 \dfrac{\Delta CG \text{ (cm)}}{\Delta t \text{ (sec)}}$

As in experiment 1, the smoothed curve of center of gravity vs. time was used to calculate the range of values of ϵ (Table 3). Again, the range of values was approximately the same, 0.022 to 0.005 ergs g^{-1} sec^{-1}, with values decreasing as the pycnocline receded from the location of mixing energy source. Thus the gradient of the pycnocline did not appear to affect the energy dissipation rate, ϵ.

Thermocline Mixing Experiment

A third mixing experiment was carried out when the near-surface temperature of a set of tanks was inadvertently raised approximately 5°C above the others by the heat exchangers (Fig. 2). The decay of the resulting temperature gradient was monitored at 25-min intervals (Fig. 7) while the mixer was operating at 4 rpm.

The method of calculating the rise of the center of gravity of the water column was again used to obtain an estimate of the minimum energy dissipation rate. The energy required to mix the water column into a homogeneous water mass was calculated to be 0.002 ergs g^{-1} sec^{-1}. Since the thermocline to be eroded was near the surface, this result agrees well with the previous experiments.

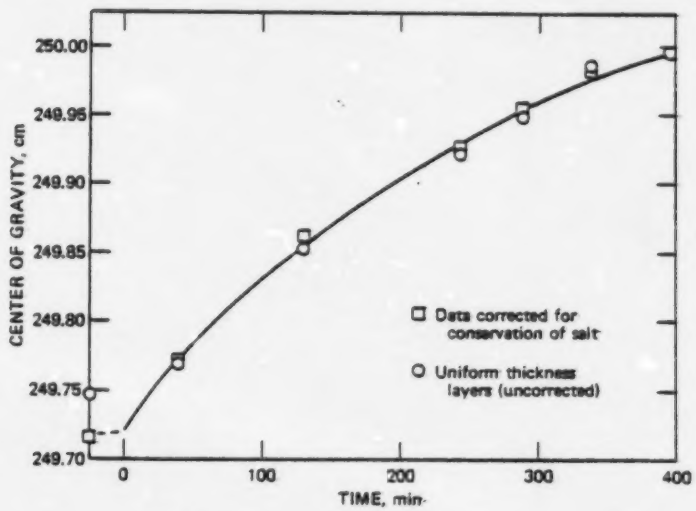

Fig. 6 Changes in location of the water column center of gravity during second pycnocline mixing experiment.

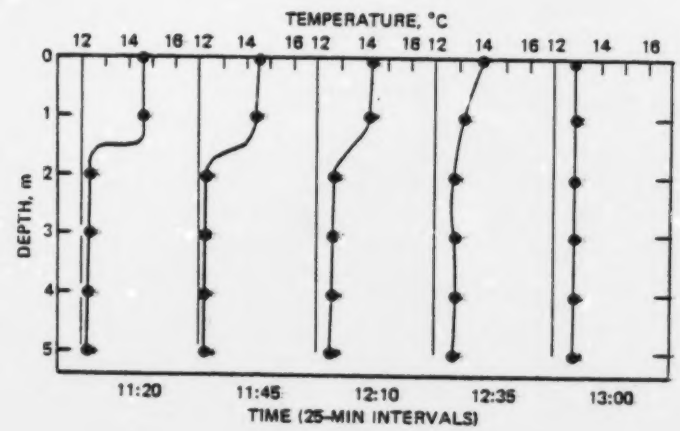

Fig. 7 Changes in temperature profiles during thermocline mixing experiment.

DYE STUDIES

Vertical Eddy Diffusivity

Dye-tracing techniques were used to estimate the vertical mixing rate in the MERL tanks. A small amount of rhodamine-WT dye solution in seawater was released instantaneously at mid-depth in the microcosms when there was little or no vertical density gradient. Water samples were collected at short time intervals (2 to 5 min) approximately 1 m from the surface and the bottom of the tank, and the concentration of dye was determined fluorometrically. The average distance traveled by a diffusing particle, such as the dye, in an ideal fluid with no boundaries is given by (Moore, 1955):

$$z^2 = 2Dt \tag{3}$$

where z is the distance traveled, D is the diffusivity, and t is time. Thus by rearranging:

$$D = z^2/2t \tag{4}$$

To estimate D_v, the vertical eddy diffusivity, we assumed that the time required for an average dye or water particle to diffuse from the middle of the tank to each end was equivalent to the time required to distribute the dye evenly from the surface to the bottom of the tanks. Since the dye was released at mid-depth, z was equal to one-half the water-column depth. Of course, the water in the MERL tanks is contained within boundaries so that the vertical eddy field is probably not entirely homogeneous in structure and the vertical eddy diffusivity may not be rigorously defined in this situation.

In general, the tanks appeared to be uniformly mixed within 10 to 20 min, with diffusivities calculated from top and bottom samples being nearly the same (Fig. 8). The results of numerous trials show that the value of D_v in the tanks with the mixer operating at 4.5 rpm is between 16 and 22 cm^2/sec. When the mixer is off, D_v decays to zero. Unfortunately, there have been no measurements of vertical eddy diffusivity in Narragansett Bay. Using a relatively well-verified numerical hydrodynamic model of circulation in the bay, Hess (1976) computed values of 1 to 10 cm^2/sec over the whole system, with an average D_v value of 5 cm^2/sec in the West Passage. Given the aspect ratio of the MERL tanks and the method of mixing, it would not be surprising if the microcosms are mixed vertically more rapidly than the bay.

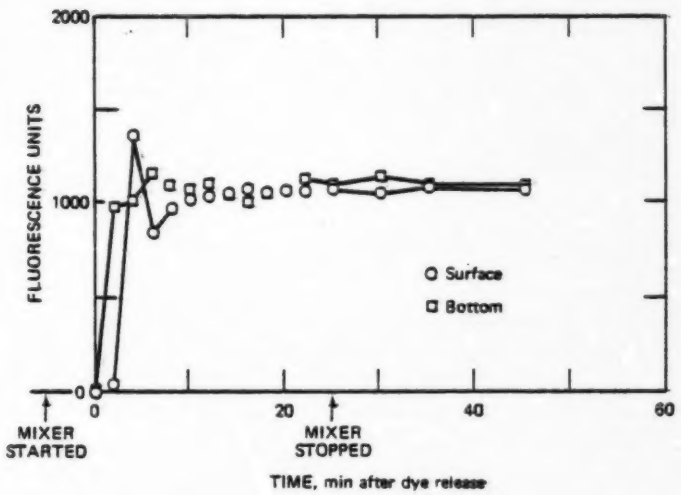

Fig. 8 Dye concentration in samples taken at near-surface and near-bottom locations in a MERL microcosm after a dye release at mid-depth.

Horizontal Spreading Rate

A relative measure of the horizontal turbulent field was obtained by creating small dye patches at various distances below the surface of the water in the bay and in the MERL tanks by use of 0.5 cm^3 of 1 : 100 rhodamine-WT dye solution in seawater. The time required for a dye patch to disperse so that it was no longer visible was measured on a number of occasions by the same observer with a stopwatch. Although the mixing device clearly increased the horizontal component of turbulence in the tanks over the unmixed condition, the rate of horizontal dye-patch spreading remained appreciably slower in the microcosms than in the bay (Table 4). This result contrasts with the relative magnitudes of vertical mixing in the tanks and in the bay. The method has been found useful for comparative studies but is clearly somewhat subjective and does not produce a value that can be related quantitatively to conventional hydrodynamic parameters.

$CaSO_4$ Dissolution Rate

A lack of firm hydrodynamic meaning is also a limitation in interpreting dissolution rate measurements although much of the

TABLE 4

RATES OF SMALL DYE-PATCH DISPERSION IN THE MERL MICROCOSMS AND IN NARRAGANSETT BAY

Location	Number of observations	Time to disperse (average ± standard deviation), sec
Narragansett Bay, West Passage (z = 20 cm)	10	18.0 ± 5.4
	6	13.4 ± 1.9
Narragansett Bay (z = 70 cm), near the mouth of the bay	6	17.5 ± 2.5
MERL tanks (mixer on standard cycle, 5.1 rpm)		
Surface	5	54.2 ± 15.3
z = 20 cm	5	71.8 ± 5.5
z = 50 cm	5	53.0 ± 11.6
z = 100 cm	7	38.6 ± 7.5
MERL tanks, mixer off (z = 20 cm)	1	⩾900

element of subjectivity is removed. Since the rate of turbulent energy dissipation will influence the thickness of stagnant boundary layers around objects in the fluid, as well as the rate of renewal of fluid just outside these boundary layers (Nixon, Oviatt, and Buckley, 1979), it is reasonable to suppose that the dissolution rate of materials should be faster in more turbulent water. After experimenting with a number of different substances, including plaster of paris, hard candy, various salts, soap, taffy, and latex balls, we found that the mineral gypsum is particularly suited to this kind of application. It is easily obtained, inexpensive, and nontoxic; does not readily exchange moisture with the air; dissolves rapidly enough in seawater to produce measurable weight losses in a few hours; dissolves slowly enough that a small block lasts for 24 hr to give a daily integration; and can be easily cut and drilled. If three to five replicate blocks (~2.5 by 1.8 by 0.7 cm and 6 to 8 g) are used in Narragansett Bay, the coefficient of variation of the mean dissolution rate during a 4- to 6-hr run is about 10%. In laboratory flume studies the coefficient of variation may range from 20% at very low flow to around 3 to 5% under rapid-flow conditions. There is a salinity effect on the dissolution rate, but this is only apparent between 0 and about 10‰. The rate is approximately 50% greater in seawater diluted to 10‰ than in fresh water, but increasing the salinity between 10 and 30‰

seems to have virtually no effect on the dissolution rate. Since, in lower Narragansett Bay and in the MERL tanks, salinity was always above 25‰, the $CaSO_4$ method was not subject to salinity effects.

The dissolution rate is also increased at higher temperatures in what appears to be essentially a linear fashion, at least between 0.5 and 28°C. In still water of 30‰, we found the following relationship:

$$D = 0.02T + 0.37 \quad (5)$$

where D is percent loss per hour, T is temperature (°C), and r^2 was 0.99. In general, however, we carried out our dissolution measurements in the bay and the MERL tanks within a few days of each other so that there was little, if any, temperature difference. The $CaSO_4$ blocks were deployed in both environments, with duplicate blocks arranged vertically in both fixed and free-floating arrays. Comparing the dissolution rate from these two modes gave the surprising result that there was little difference between them. In fact, statistical analysis showed that rates from the free-floating arrays were significantly ($P = 0.05$) higher than those from fixed arrays. Such a comparison is complicated since free-floating arrays moved with a water mass and thus experienced a different environment from those that were held in place. The results do suggest, however, that the dissolution rate may respond more strongly to small-scale turbulent effects than to mean flow. Although more work on the calcium sulfate block method is needed, the results so far are encouraging for its use as a simple measure of relative turbulence. Representative vertical profiles of dissolution rates in the MERL tanks and in Narragansett Bay are given in Fig. 9. Again, as with the dye-patch spreading rates, the blocks indicate that the turbulence level in the microcosms is appreciably lower than that in the bay when averaged over 6 to 24 hr.

Neighbor Diffusivity and Turbulent Energy Dissipation

Richardson (1926) first described a relationship between turbulence and scale that distinguished between classical Fickian diffusion (in which scale is not a factor) and the mixing that is characteristic of turbulent fluids such as the sea. Although the nature of turbulence is extremely complex, Richardson's concept of turbulent energy passing through a series of successively smaller eddies from the wavelength at which it is put into the system until it is ultimately dissipated in viscosity has continued to prove useful in studying the mixing of marine waters (Okubo, 1971).

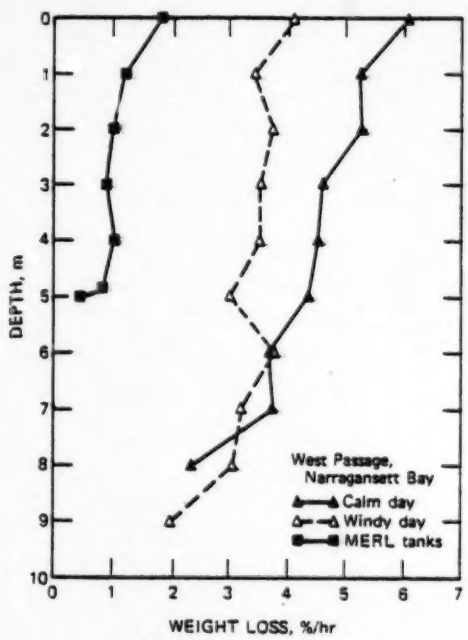

Fig. 9 Comparison of $CaSO_4$ block dissolution rates in Narragansett Bay and in the MERL microcosms during mixing, March—April 1977.

As a consequence of turbulent mixing, floats placed in the sea will separate more rapidly the further apart they are. The relationship between distance and spreading rate was formalized by Richardson (1926), Stommel (1949), and others in the concept of neighbor diffusivity, a parameter characteristic of turbulent fluids that is roughly analogous to classical molecular diffusivity. It is also possible to use observations of the relationship between spreading rate and scale to calculate the flux of turbulent energy according to an analysis given by Batchelor (1950):

$$F = \left(\frac{\overline{l_{x_2}^2 - l_{x_1}^2}}{2t}\right)^2 \tag{6}$$

$$\epsilon = \left\{\frac{(l_{x_2}^2 - l_{x_1}^2)/t}{2t[1 + \frac{1}{3}\,(l_{x_1}^2/l_0^2)]^{\frac{1}{3}}\, l_0}\right\}^{\frac{3}{2}} \tag{7}$$

where F = neighbor diffusivity for groups of floats with an average separation during the measurement of $(l_{x_1} + l_{x_2})/2$
ϵ = rate of turbulent energy flux
l_0 = initial scalar distance between floats
l_{x_1} = initial distance between floats projected on an arbitrary x-axis
l_{x_2} = distance between floats after some time, t, projected on the x-axis
t = time

Data for calculating F and ϵ were obtained by releasing several dozen floats and photographing them from a fixed position at short time intervals. The size of the floats used and the length of the time interval were adjusted according to the scale of the turbulent eddies of interest. In the West Passage of Narragansett Bay, large-scale mixing (1 to 25 m) was studied with colored balloons filled with fresh water so that they floated just beneath the surface. These floats were dispersed from a small boat and photographed every few minutes from a high bridge. Small-scale eddies (1 to 200 cm) were studied in the field with small (~0.5 cm) colored plastic beads that were released from the end of a pole off the stern of a small boat and photographed every few seconds with a 16-mm movie camera operated from the flying bridge of the boat. The beads and the movie camera were also used in the microcosms. In all cases floating rods of standard length were included in each photograph to give an accurate scale.

The films of the floats were developed and put through a microfiche reader for enlargement. Large numbers of pairs of floats (~100) were selected at various distances of separation to be followed from frame to frame over time. In each frame the scalar distance between the floats, as well as their separation along two perpendicular vectors (x and y), was obtained. Calculating F and ϵ from the x- and y-coordinates should yield similar values if the turbulent field is isotropic, a basic assumption of the model leading to the derivation of the formulas.

Neighbor diffusivity was a function of scale in the MERL microcosms and in Narragansett Bay, with F increasing roughly in proportion to the $\frac{4}{3}$ power of l, as suggested by the theoretical analysis given by Richardson (1926), Stommel (1949), and others (Fig. 10). However, the large amount of scatter in the data makes it difficult to present a convincing statistical argument about the magnitude of turbulence in the two systems. This was also true for the calculation of turbulent energy dissipation in the bay and in the

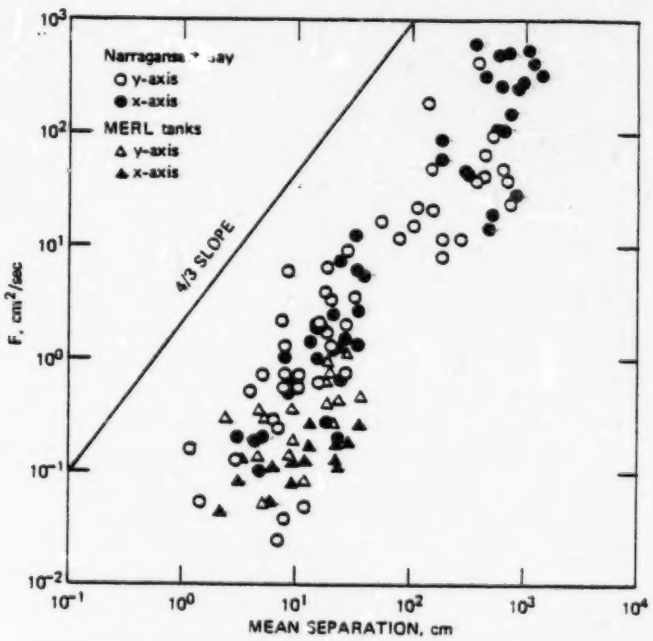

Fig. 10 Neighbor diffusivity, F, calculated from paired float-separation measurements showing correlation with mean separation distance.

tanks (Table 5). Our interpretation is that the variance in the paired-float data reflects the stochastic nature of turbulent processes and may limit the practical application of the method in problems requiring rigorous definition of turbulent energy dissipation rates. For our purposes the mean values from approximately 100 sets of paired floats in each system provide a useful measure of relative turbulence levels. In general the microcosms appear less turbulent than Narragansett Bay. The x- and y-coordinates could not be separated statistically in either system, and the mean values appear similar in the MERL tanks. In the West Passage, however, the mean ϵ values for the x-axis appear higher than those for the y-axis in three out of the four complete analyses (Table 5). This may reflect the fact that the x-axis was parallel to the main tidal flow in the West Passage, whereas the y-axis was perpendicular to it.

Unfortunately, the paired-float measurements apply directly only to the surface water. Despite the uncertainties involved in both this approach and that of the pycnocline mixing experiments, it is

TABLE 5

ESTIMATES OF TURBULENT ENERGY DISSIPATION RATES IN THE MERL MICROCOSMS WITH PAIRED FLOAT-DIVERGENCE MEASUREMENTS*

	ϵ, ergs g^{-1} sec^{-1} (average ± standard deviation)	
	x	y
MERL microcosms, estimated from paired floats with plunger operating	0.001 ± 0.005	0.002 ± 0.009
Narragansett Bay, West Passage		
Measured at different times with paired floats	0.361 ± 4.65	1.02 ± 1.32
		0.022 ± 0.235
	0.002 ± 0.182	
	0.058 ± 0.260	0.010 ± 0.103
	0.182 ± 0.214	0.037 ± 0.151
	0.289 ± 0.317	0.072 ± 0.272
Overall mean for bay floats	0.253	

*The x and y are orthogonal horizontal axes with arbitrary orientation.

encouraging to note that the two methods agree remarkably well in setting turbulent energy dissipation rates at the surface between 0.001 and 0.002 ergs g^{-1} sec^{-1} (see Tables 2, 3, and 5 and Fig. 4).

Gas-Exchange Measurements at the Air–Water Interface

The simplest model for gas exchange across the air—water interface proposes that the flux is limited by molecular diffusion through stagnant films in the gas and the water phases at the interface. It presumes that the air above and the water below these films are well mixed and that the gas is unreactive with the water. Since the molecular diffusion coefficient for a gas in the water is much smaller than that in the air, the exchange is limited by the diffusion in the water, and the stagnant film in the air can be neglected. Such is the case for oxygen; its molecular diffusion coefficient in water is 10^{-4} times that in air (Liss, 1973). Thus the flux of gas across the stagnant film can be described by (Liss, 1973):

$$J = K(C_s - C_w) \tag{8}$$

$$K = \frac{D}{Z}(10^{-4}) \tag{9}$$

where J = gas flux ($\mu g\ cm^{-2}\ hr^{-1}$)
K = exchange coefficient (cm/hr)
C_s = concentration of the gas at the top of the stagnant film in equilibrium with the air ($\mu g/cm^3$)
C_w = concentration of the gas at the bottom of the stagnant film in equilibrium with the underlying water ($\mu g/cm^3$)
D = molecular diffusion coefficient of the gas at a certain temperature (cm^2/hr)
Z = stagnant film thickness (μm)

Although the existence of a discrete stagnant film seems physically simplistic, results obtained from Eq. 9 are essentially the same as those obtained from more elegant models based on film renewal (Danckwerts, 1970). The film-renewal concept can be readily associated with turbulence in the water. As turbulence in the water is increased, the water just below the imaginary stagnant-film boundary layer will be renewed more rapidly, with the renewal rate given by (Monin and Yaglom, 1975):

$$R \approx \left(\frac{\epsilon}{\nu}\right)^{1/4} \tag{10}$$

where R is the renewal rate per second, ϵ is the energy dissipation rate (cm^2/sec^3 or ergs $g^{-1}\ sec^{-1}$), and ν is the kinematic viscosity (cm^2/sec). This increase in renewal rate tends to maximize the gradient in concentration of gas across the boundary layer and, thus, the diffusion of material across the layer. Also, the increase in renewal rate by increased turbulence will decrease the thickness of the boundary layer itself, according to the following relation (Monin and Yaglom, 1975):

$$Z \approx \frac{1}{\sqrt{R}} \approx \left(\frac{\epsilon}{\nu}\right)^{-1/4} \tag{11}$$

Again, the effect will be to increase the diffusion rate at higher values of ϵ.

The net flux of gas across the interface where a concentration gradient exists can be measured experimentally. The thickness of the hypothetical stagnant film can be calculated since the molecular diffusion coefficients of many gases are known. Liss (1973) suggested that experimental results be reported as exchange constants, K or D/Z, in centimeters per hour. We report our data in both forms.

The flux measurements were made with a floating plastic dome that had been flushed with N_2 gas (Roques and Nixon, in

TABLE 6

ESTIMATES OF GAS EXCHANGE AT THE AIR–WATER INTERFACE IN NARRAGANSETT BAY AND IN THE MERL MICROCOSMS*

	K, cm/hr	Z, μm
Narragansett Bay		
Wind, 1.8 m/sec	4.2	176
Wind, 2.8 m/sec	9.2	80
Wind, 3.3 m/sec	12.3	60
MERL microcosms		
Mixer off	0.6	1167
Mixer on (~5 rpm)	1.4	514
On–off standard cycle:		
from oxygen dome	1.0	730
from radon†		693 ± 85

*Data from Roques and Nixon (in preparation), ~20°C.

†Data from Santschi, Li, and Broecker (1978), average ± 1σ.

preparation). The partial pressure of oxygen in the dome and the water was monitored over time, and the flux of gas across the air–water interface was evaluated as a function of the concentration gradient. From these data we could calculate K and Z for both Narragansett Bay and the MERL tanks. Measurements were made in the bay under a variety of conditions and in the tanks with the mixer off and with it running at normal speed. In the MERL tanks the estimate of stagnant-film thickness obtained from the dome measurements of oxygen flux could be compared with independent estimates of film thickness made by Santschi, Li, and Broecker (1978), who used a radon addition to the tanks. Again, the results document the effect of the mixer in increasing the turbulence level of the microcosms but suggest that the levels obtained in the tanks are below those of the natural system (Table 6).

DISCUSSION

With the exception of vertical eddy diffusivity, mean values of all the turbulence measurements were greater in Narragansett Bay than in the MERL microcosms (Table 7). A number of parameters,

TABLE 7

SUMMARY OF TURBULENCE MEASUREMENTS IN THE MERL MICROCOSMS AND IN NARRAGANSETT BAY

Turbulent Energy Dissipation	
	ϵ, ergs g^{-1} sec^{-1}
Narragansett Bay, West Passage, with paired floats	
Surface mean	0.253
Range	0.002—1.02
MERL tanks, standard mixer on at 4—5 rpm	
Paired floats (surface)	0.001—0.002
Pycnocline mixing (surface)	0.002
Near mixer	0.06
Mean	0.03
Direct estimate of water mass swept by plunger	0.21
Vertical Eddy Diffusivity	
	Dv, cm^2/sec
Narragansett Bay, West Passage (Hess, 1976)	5
MERL tanks	
Standard mixer on at 4.5 rpm	16—22
Mixer off	Decays to 0
Rates of Horizontal Dye-Patch Dispersion	
	Time to disperse, sec
Narragansett Bay, West Passage, near surface	8—18
MERL tanks	
20 cm depth	72
50 cm depth	53
$CaSO_4$ Dissolution Rate	
	Weight loss, %/hr
Narragansett Bay, West Passage	
Stationary, vertical profile	7.7—10.2
Free floating, vertical profile	6.1
MERL tanks, stationary, vertical profile	1.2—1.6
Air—Sea Gas-Exchange for O_2	
	Stagnant-film thickness, μm
Narragansett Bay, West Passage, with varying wind speeds	60—176
MERL tanks	
Standard mixer on	514
Mixer off	1167

TABLE 8

ESTIMATES OF TURBULENT ENERGY DISSIPATION IN NARRAGANSETT BAY AND SOME OTHER NATURAL MARINE WATERS

	ϵ, ergs g^{-1} sec^{-1}
Narragansett Bay, West Passage	
Paired floats	0.25
Tidal currents (Levine and Kenyon, 1975)	0.06*
Irish Sea, tidal currents (Taylor, 1919)	0.08
Northwest Pacific coastal water, U.S.A., surface 30 m, calculated from changes in microstructure (P. W. Nasmyth in Gregg, 1973)	0.02
Open sea, surface mixed layer (50 m) (Gregg, 1973)	0.002

*This estimate is for total energy input, including bottom friction losses and work by the bay on the moon, neither of which add to turbulent energy dissipation in the water itself. The input of wind to turbulent mixing in the water was not included, however. A water mass of 6.78×10^{14} g was assumed for the West Passage (Kremer and Nixon, 1978).

however, including energy dissipation rates (Table 5), gas-exchange coefficients (Table 6), and neighbor diffusivity (Fig. 10), showed considerable variation in the field. As far as can be determined from the present data, the turbulent mixing obtained in the microcosms is likely to fall generally at the low end or below the range of mixing conditions found in the bay. The average turbulence levels found in Narragansett Bay are probably higher than those characteristic of many other coastal waters or the open sea (Table 8). Some caution must be used in comparing different values of ϵ reported in the literature, however, because of the different methods of measurements used and the large variance associated with this parameter, particularly in coastal environments. For example, the paired-float estimates for surface water in the bay appear to give a somewhat higher value for turbulent energy dissipation than the estimate of Levine and Kenyon (1975) of tidal energy inputs in the bay (Table 8). Their value does not include the input of turbulent energy near the surface from wind, however. Within the MERL tanks

TABLE 9

ENERGY FLOW OF VARIOUS KINDS IN NARRAGANSETT BAY AND THE MERL MICROCOSMS

	Energy flow, kcal m^{-2} $year^{-1}$	
	Narragansett Bay	MERL
Solar radiation*	1.23×10^6	
Primary production†	$2.6–3.1 \times 10^3$	$\sim 2.7 \times 10^3$
Turbulence‡	$0.7–1.4 \times 10^3$	7.5–38

*Pyrheliometer from Eppley Laboratories, Newport, R. I.

†Narragansett Bay = 260–310 g C m^{-2} $year^{-1}$ (Furnas, Hitchcock, and Smayda, 1976; Oviatt, personal communication)
MERL = ~270 g C m^{-1} $year^{-1}$ (Oviatt, personal communication)

Assuming 4.5 kcal/g dry weight of organic matter and a composition of 45% carbon by weight.

‡Narragansett Bay lower estimate from Levine and Kenyon (1975), upper from paired floats. MERL lower estimate from surface paired floats, upper from mean value in the water column during a mixing experiment.

themselves, ϵ can be taken as about 0.21 ergs g^{-1} sec^{-1} by direct calculation from the operation of the mixer, as 0.03 ergs g^{-1} sec^{-1} from a geometrical average of the exponential decay of turbulence with distance from the plunger during a halocline mixing experiment (Fig. 4), or as 0.002 ergs g^{-1} sec^{-1} from paired-float measurements at the surface (Table 7). When averaged over a day, the MERL values should all be reduced to about one-third of those values because of the standard 2-hr-on and 4-hr-off mixing schedule.

To gain some perspective on the magnitude of energy flow associated with turbulence in Narragansett Bay and in the MERL microcosms, we should compare the values of ϵ in these systems with other energy inputs, such as solar radiation and photosynthetic production. For convenience, we have converted the turbulent energy dissipation rates reported earlier from ergs per gram per second to kilocalories per square meter per year, a more conventional ecological reference. The results suggest that the flow of chemical energy through biological food chains is considerably greater than the flow of physical energy through turbulent eddies (Table 9). Assuming that virtually all the photosynthetically fixed energy is consumed in one way or another during the annual cycle, the average

rate of biological energy dissipation is 2 to 4 times greater than the rate of turbulent energy dissipation in the bay. The corresponding ratio in the MERL tank appears to be between 70 and 360.

Despite this discrepancy, after more than 2 years of operation, we have no reason to believe that any of the biological or chemical components of the MERL microcosms are behaving anomalously as a result of the apparently lower mean turbulence levels in the tanks than in the bay. Overall, the MERL microcosms have developed self-maintaining ecosystems whose complex seasonal behavior over an annual cycle is strikingly similar to the natural system (Pilson et al., 1977, 1979, and this volume; Marine Ecosystems Research Laboratory, 1979). If the ecology of pelagic systems is significantly influenced by the turbulent energy dissipation rate (see, e.g., Nixon, Oviatt, and Buckley, 1979), then the correspondence between the behavior of the microcosms and Narragansett Bay, even though the turbulence level in the tanks was much less, suggests that the systems are relatively insensitive to changes in turbulent energy input within the ranges observed in these experiments.

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